Global Monitoring of Ionospheric Total Electron Content Using the IGS Network

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ABSTRACT

The GPS satellites and a world-wide network of dual-frequency GPS receivers allow one to measure ionospheric total electron content (TEC) on global scales. This paper describes a method for generating global ionospheric maps (GIM) using data from the IGS network. Our method uses a Kalman-type filter and random-walk process noise to generate global TEC maps at time intervals of one hour or less. The accuracy of the maps has been assessed by comparing the computed vertical TEC to independent measurements from the dual-frequency altimeter onboard the TOPEX/POSEIDON ocean altimetry satellite. Computed root-mean-square (RM S) difference.s between global ionospheric maps and TOPEX arc 4 TECU (1 TECU = 1 x 1016 el/m^2) when the TOPEX ground track comes within 500 km of a GPS receiver, Comparisons along the entire TOPEX track generally yield larger RMS differences (5–1O TECU), indicating that the global maps become less accurate in regions far from GPS receivers.

1. IN'1'RODLJCTION

The IGS global network currently consists of more than 60 high--precision dual-frequency global positioning system (GPS) receivers distributed around the world. Data from this network has been used to produce global ionospheric maps (GIM) which are "snapshots" of the Earth's zenith total electron content (TEC) distribution [Mannucci, et al. 1993]. Global ionospheric maps are useful for monitoring the global TEC distribution for scientific studies, model development and calibration of ionospheric delay.

in addition to the GPS network, vertical TEC measurements covering a significant portion of the Earth's oceans are available from instruments onboard the TOPEX/POSEIDON ocean altimetry satellite. These instruments include a dual-frequency ocean altimeter and a dua]-frequency range rate (DORIS) capability. The TOPEX data can be used to study the accuracy of tile GPS-based global maps, or incorporated into the mapping algorithm to improve accuracy. 1 n this paper, we present a preliminary assessment of the accuracy of the global maps by performing comparisons between the mapped TEC and the ionospheric measurements available from the dual-frequency altimeter.

First, we review the factors which affect the accuracy of the global maps (see *Mannucci et al. 1993*, for a more complete description of the technique). After a brief discussion of the altimeter data type, a preliminary study of the global map accuracy will be presented, based on comparisons to the TOPEX data. Finally, we will summarize and indicate what follow-on studies arc being pursued.

2. THE GIM MODEL

The GPS receivers in the global network measure line-of-sight total electron content between a receiver and up to 8 GPS satellites simultaneously. To form a global map, the GPS measurements arc converted to equivalent vertical values and a grid-based algorithm is used to interpolate between the individual TEC measurements. In some geographic regions, the nearest receivers arc thousands of kilometers away (see figure 1). Therefore, the interpolation must work. locally near each receiver and globally between receiver groups, and the accuracy of the maps arc likely to vary with distance from the GPS receivers.

GPS Global Network 1995 -- 54 Rogue-Type GPS Stations
Receivers: 20 Rogues, 34 TurboRogues. Note:14 Stations in Southern Hemisphere
JPL/NASA owned o roperated stations underfined (19 Receivers or 35% of the Network)

Figure 1: Locations for the GPS receivers in the global network.

The global mapping technique uses a linear least squares parameter estimation procedure. The instantaneous ionospheric state is specified by estimating the TEC at a set of 642 fixed grid points on an "ionospheric shell" at a height of 350 km. The TEC values are related to a GPS observation as follows:

$$I_{rs}(t) = F(E) \sum_{i=1}^{3} W_i(\phi_{pp}, \lambda_{pp}) V_i + b_r + b_s \tag{1}$$

where $I_{rs}(t)$ is the GPS line- of-sight measurement from receiver r and satellites at t imc t, V_i is the value of the TEC at vertex i (i .e. parameter i), and b_r and b_s arc the receiver and satellite instrumental delays [Wilson *and Mannucci, 1993*]. The placement of the vertices is based on a triangular tessellation of a spherical shell. The factor $W_i(\phi_{pp}, \lambda_{pp})$ is a weighting function which depends on the distance between vertex i and the ionospheric pierce point of the measurement, whose latitude and longitude is $(\phi_{pp}, \lambda_{pp})$. Each measurement only affects the three vertices of the intersected tile. $F(E)$ is the elevation mapping function relating slant delay to vertical. The simplest "thin-shell" mapping function is given by:

$$F(E) = \left\{ 1 - [\cos]; / \,(1 + h / R_E)]^2 \right\}^{-\frac{1}{2}} \tag{2}$$

where E is the elevation angle, h is the height of the shell (350 km) and R_E is the mean Earth radius. There arc several more realistic mapping functions which can still be expresssed analytically in closed form, including a uniform slab of finite width and an extended slab (a slab with exponential tails).

A Kalman-type filter is used to estimate the vertex and instrumental bias parameters based on the linear observation equation 1. The vertex parameters are re-esti mated every hour (more frequent updates are possible) allowing the maps to follow short term TEC changes of the ionosphere. An animated sequence of maps can show the time evolution of the global ionosphere. The errors for vertex values not updated with new data grow as a random walk (square root of time).

Local to each GPS receiver, the accuracy of the maps is affected by multipath noise at low elevations; the accuracy of the instrumental bias determinations for the GPS receivers and satellites; errors made in the elevation mapping function; and errors of interpolation between the ionospheric pierce points of the GPS measurements (some of these factors arc discussed by *Klobuchar et al.,*1993).

The large-distance interpolation between the local GPS measurements is made more accurate by fixing the grid points in a "solar-geomagnetic" coordinate system. in this system, each vertex has a fixed geomagnetic latitude and nearly sun-fixed longitude, so the grid does not co-rotate with the Earth. The value of a grid point represents the TEC value for a given local time, not a given geographical position. All geographic regions, whether populated with GPS stations or not, sample the full range of local times over the course of a day. Therefore, in areas far from receivers, the TEC value at a given local time is determined by measurements obtained at that same local time from receivers in a geomagnetic latitude band surrounding the vertex. In effect, interpolation of the distribution over large distances is replaced with "local. time prediction".

3. TOPEX COMPARISONS

3.1 The TOPEX dual-frequency altimeter

To assess the accuracy of the GPS-based global maps, we used the ionospheric measurements from the TOPEX dual-frequency radar altimeter (TPXALT). This data set, available from the satellite since October of 1992, measures vertical TEC up to a height of about 1330 km, which is above almost all of the daytime ionosphere. Since the global ionospheric maps (GIM) provide vertical TEC covering all latitudes and times, the GIM evaluated along the TOPEX ionospheric pierce points can be compared to the altimeter measurements. An example of such a comparison plot is shown in Figure 2. The TOPEX orbital period is approximately 110 minutes.

3.2 Comparison Overview

The TOPEX/GIM comparison has been done in two ways. First, we have restricted the comparisons to times when the TOPEX ground track comes within 500 kilometers of a GPS station (a so-called "over-flight"). This tests the accuracy of the maps local to a GPS receiver. We have also compared the GIM and TOPEX measurements over the entire clay-time portion of each ground track. The TOPEX altimeter data is only available over the water, where the average distance to the nearest station is typically several thousand kilometers. Therefore, the whole track comparisons assess the accuracy of the interpolation in areas far from GPS receiver sites.

Data from three periods was used in this study: March 13-15 of 1993, August 13-15 of 1993 and January 23, **24,** 26 and **27** of 1994. The station locations for the current network are shown in Figure 1. The global geomagnetic index Ap for each day is shown in Figure 3. All comparisons were performed for local daytime (6 am-6 pm) conditions so that the accuracy numbers represent an upper limit (undiluted by the low nighttime TEC Values).
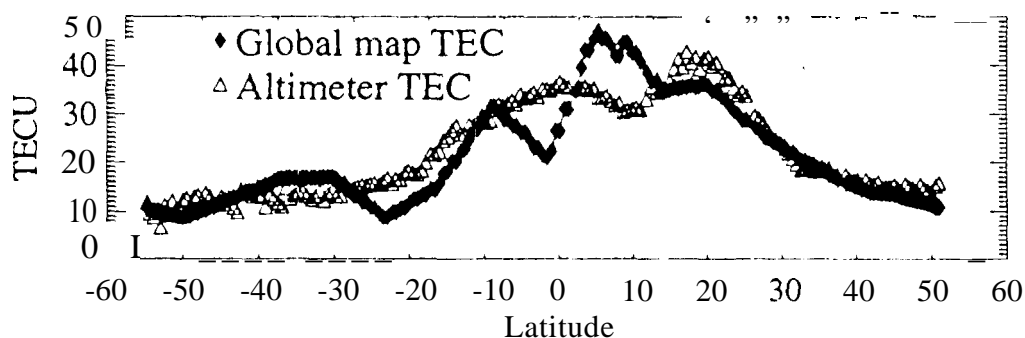
Figure 2: A plot showing the TOPEX-derived TEC measurements and the GIM map evaluated along the TOPEX track. Data from August 14, 1993 is shown. The track was at its southern-most point at 13:00 local time and crossed the equator at 16:25 local time.

3.3 over-flight analysis: assessing GIM near GPS receivers

Comparing GIM and TPXALT during over-flights allows a comparison between the "instantaneous" ionosphere measured by each technique with a minimum of interpolation error. An over-flight occurs when the TOPEX ground track comes within 5 degrees (500 kilometers) of a GPS receiver; 36 daytime over-flight opportunit ies from 18 receiver sites were analyzed, and the results for mid and low latitude sites arc summarized in Table 1. The nine mid-latitude sites used in this study were situated between 30 and 55 degrees, north or south. The nine equatorial sites were within 30 degree.s of the geographic equator. The RMS differences were computed between the GJM TEC values and the TPXALT measurements for every 10 second altimeter data point during the 1-2 minute duration of each over-f] ight.

	Low Latitude	Mid Latitude
RMS Difference	4.0	4.1
Mean Difference	--1.9	-3.5

'J'able 1: RMS and mean differences between TPX ALT and GJM for 36 over-flight opportunities in March and August of 1993 and January of 1994. Vertical TEC differences in units of TECU.

The RMS difference between the GPS and TOPEX-deri ved TEC is about 4 TECU, and dots not differ for the two latitude bands ($1\,TECU = 1\,TEC$ unit $= 1 \times 10^{16}$ cl/m^2). Some contribution to this RMS difference is due to the finite accuracy of the TOPEX measurements, estimated to bc about 3 TECU [Callahan, 199.?]. If the TPXALT and GJM errors arc summed in a root-sum-square manner, then a global map error of 2.6 TECU **near** the receivers **is consistent** with a TPXALT error of 3 TECU and an overall RMS difference for the over-flights of 4.0 TECU.

The negative mean difference between GIM and TPXAl .1' indicates that the global map TEC was on average lower than the altimeter-dc.rived TEC. This is surprising since the GPS satellites orbit at 22,000 km altitude while the TOPEX altitude is 1330 km. Onc possibility is that the TOPEX altimeter TEC data is biased too high. Another possible explanation is that the estimates for the GPS receiver or satellite instrumental delays are larger than the true values. Since the bias between two independent measurement types is an upper limit on the accuracy of each technique, agreement at the level of 2–3.5 TECU is encouraging and suggests that the estimated instrumental delays for the GPS receivers and satellites arc accurate to at least that level. The GPS instrumental bias estimates may improve in the near future with the use of an improved elevation mapping function.

For these over-f]ights, the satellite and receiver instrumental biases were estimated along with the TEC distribution for all but three receivers. The receiver biases in Goldstonc, California, Madrid, Spain and Tidbinbilla, Australia were fixed to hardware calibration values. Of these three, only the Tidbinbilla station was used in the over-flight comparisons,

3.4 Accuracy comparison along the TOPEX orbit as a function of latitude band

The TEC differences between GIM and TOPEX along the entire daytime portion of the TOPEX orbits have also been computed. The orbital ground tracks span a latitude range of approximately 66S to 66N geographic and have a Sun-relative angle (local time) that varies only about 2 degrees per day. The differences have been analyzed as a function of latitude region. We expect local-time prediction to be less accurate in the low latitude region where the ionospheric F2 layer is more variable than for the mid-latitudes. Another latitude-dependent factor which may affect accuracy is the number of sites in each latitude band: there are more northern mid-latitude sites as compared to the low and southern mid-] latitudes.

Figure 3 shows the RMS differences between GIM and TOPEX as a function of latitude band for the three time periods studied. As expected, the RMS differences along the entire track are generally larger than for the over-flights. This results from the additional interpolation error required to produce GIM values far from the stations. For most days, the low latitude band contains the largest RMS differences.
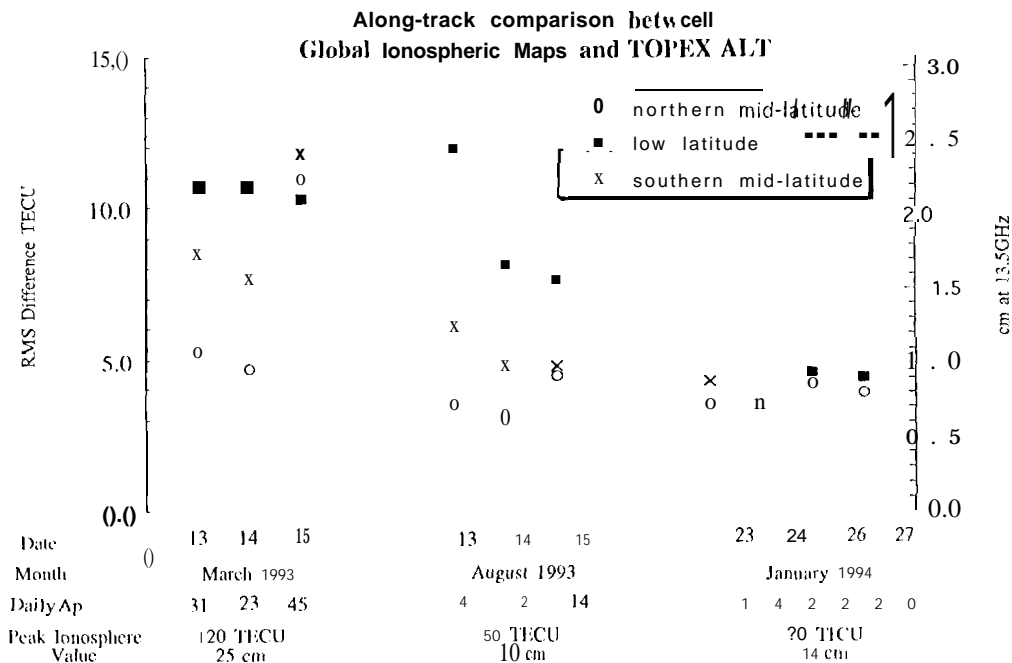
Figure 3. Daily RMS differences between TPX ALT and GIM along the entire daytime portion of the altimeter ground track. The latitude bands are defined as follows: northern mid-latitude = 60N-30N geographic; low latitude = 30N-30S; southern mid-latitude = 30 S-60S.

The RMS error for each latitude band decreases going from March 1993 to January 1994. This is not surprising since the number of stations in the network increased from March to January. However, the differences in the RMS errors are probably related to the differences in local times for the three periods. The daytime TOPEX passes were around local noon during March 1993, 4:30 PM local time during August 1993, and 8 AM during January 1994. The number of days studied is too few to draw any firm conclusions. The accuracy of the global maps is a function of the number and distribution of the receiver sites and the temporal variability of the ionosphere, which tends to reduce the accuracy of local-time prediction.

4. CONCLUSION

This study is a preliminary effort to assess the accuracy of the global ionospheric maps. Since the TEC data available from the altimeter onboard the TOPEX/POSEIDON satellite covers a broad range of latitudes, it is a valuable tool in such a study. Unfortunately, no data is available above 66 degrees latitude due to the satellite inclination and no data is available over land.

A comparison between GIM and TOPEX was done for "over-frights", when the TOPEX ground tracks came within S00 km of a GPS receiver. This comparison reveals an RMS difference between TPXALT and GIM of about 4.0 TECU. The results are the same for equatorial and mid-latitude over-flights. Given that the TOPEX accuracy is considered to be about 3 TECU, the RMS error of the vertical TEC measured by GIM near the receivers may be 2.6 TECU.

The global maps were also compared to the TOPEX measurements along the entire daytime portion of the TOPEX orbit for three latitude ranges. As expected, the RMS differences were generally larger than for the over-flights and were usually larger in the low latitude region than in the mid-latitudes. Since several factors contribute to the accuracy of the global maps, a more comprehensive study is in progress to analyze how the accuracy varies as a function of local time, geographic region, distance from the receivers, and geophysical conditions.

ACKNOWLEDGMENTS

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